Prince George Forest Region

Forest Resources & Practices Team

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FOREST RESEARCH NOTE

EXPERIMENTAL PROJECT 660 - 30 Year Progress Report for the Bobtail Road Installation, Cluculz Lake

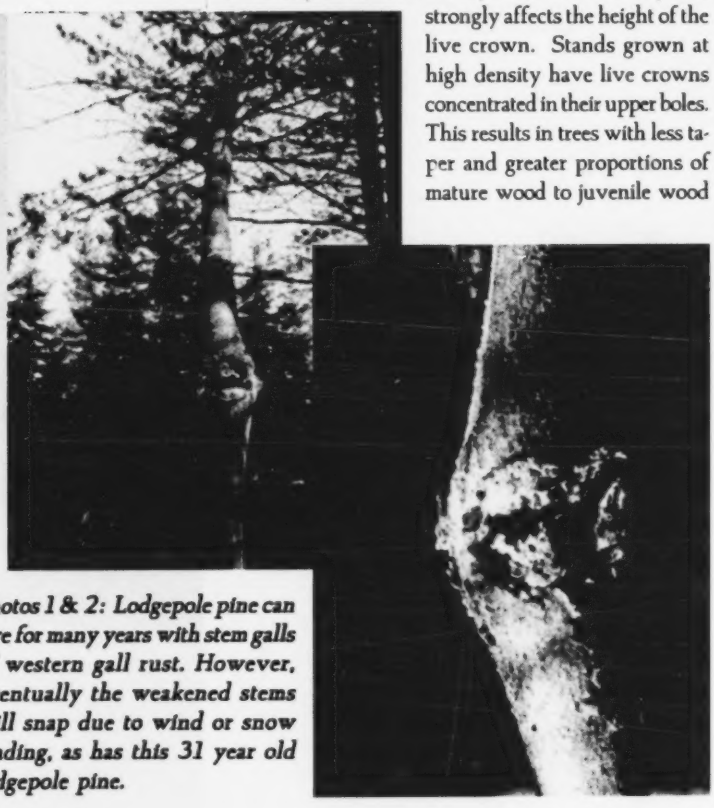
Dave Coopersmith, Bruce Rogers and Vera Sit

The influence of planting density on the early performance of three sub-boreal tree species in the Prince George Forest Region

Introduction

The choice of which tree species to plant following harvest and the density of planting are fundamental choices by foresters at the beginning of a rotation. These choices will influence not only the future options available to foresters, but also many of the final outcomes at subsequent harvest. They are also the two factors most easily controlled by the forester (Daniel *et al.* 1979).

Plantation density is know to have the greatest initial effect on mean tree size (quadratic mean diameter or QMD, also known as average stand diameters) and subsequently, if densities are high enough, on final yield at rotation (Daniel *et al.* 1979). However, density also strongly affects the height of the live crown. Stands grown at high density have live crowns concentrated in their upper boles. This results in trees with less taper and greater proportions of mature wood to juvenile wood when compared to trees grown at lower densities. It is rare in the Prince George region for target stocking densities to go above 1200 stems per hectare (sph) (Anonymous 1993). Stands that are grown at densities of 1200 sph and lower usually have very large live crowns, maintain live branches for long periods of time on the lower bole and have large branch diameters. Daniet *et al.* (1979) have noted that large branch diameters is one of the major causes of degrade in lumber produced from second-growth stands. It is also the one stand characteristic that can be controled at planting or manipulated through silvicultural treatments.



Photos 1 & 2: Lodgepole pine can live for many years with stem galls of western gall rust. However, eventually the weakened stems will snap due to wind or snow loading, as has this 31 year old lodgepole pine.

Relative to other areas of British Columbia (BC) with more southern or coastal climates, foresters working in boreal and sub-boreal forests of north-central BC have relatively few species of conifers to choose from. More than 97.4 per cent of all the planting within the Prince George Region is accomplished with only two species; interior white spruce (*Picea glauca* [Moench] Voss) and lodgepole pine (*Pinus contorta* Doug. *ex.* Loud.) (Anonymous 1997). Together, these two species represent only 74.16 per cent of the volume of billed stumpage within the region. Other species such as Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), sub-alpine fir (*Abies lasiocarpa* [Hook.] Nutt.), western red cedar (*Thuja plicata* Donn *ex* D. Don in Lamb.) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) are under-represented in the numbers of seedlings replanted versus their billed volumes. We can interpret these data as indicative of a bias towards species which are know to have very fast initial growth following outplanting. Tree species that lack fast initial growth, those which have real or perceived problems at establishment with frost and other abiotic site factors, or those species which are utilised so seldom that little operational experience in growing or planting them exists have traditionally been avoided in the Prince George Region.

The bias towards fast initial height growth is understandable. In BC silviculture prescriptions must specify time lines for stands to reach a "free growing" condition following harvesting. A free growing stand is defined as "a stand of healthy trees of a commercially valuable species, the growth of which is not impeded by competition from plants, shrubs or other trees" (Anonymous 1995). Species with slower initial height growth will take longer to reach the minimum heights necessary to be declared free growing, or may require additional silvicultural treatments to reach free growing.

This bias towards tree species that display fast initial growth may have unforeseen consequences. While species such as lodgepole pine do display fast initial growth, the differences in overall growth rate between fast inital growth species and those species which grow slower initially often decrease with time (Bella and De Franceschi 1974). Species which display very fast initial growth also tend to be highly susceptible to pest and pathogen problems (e.g. red squirrel [Sullivan *et al. 1996]* and western gall rust [Van der Kamp 1981] damage to young lodgepole pine stands). Very often these agents damage trees well past the age that free growing is declared (photos 1 & 2). Other species may indeed have slower initial growth, but offer much greater resistance to pests and pathogens. Over the course of a rotation it may be that resistance to a wide range of pests, pathogens and abiotic damage is much more important for the achievement of management objects than is initial growth rate

Experimental Project (EP) 660 is a long-term plantation study examining the influence of planting density (espacement) on the growth performance of white spruce (*Picea glauca* [Moench] Voss), Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) and lodgepole pine (*Pinus contorta* Doug. ex. Loud.). Established in 1967, this study is one of the oldest plantation studies in northern BC.

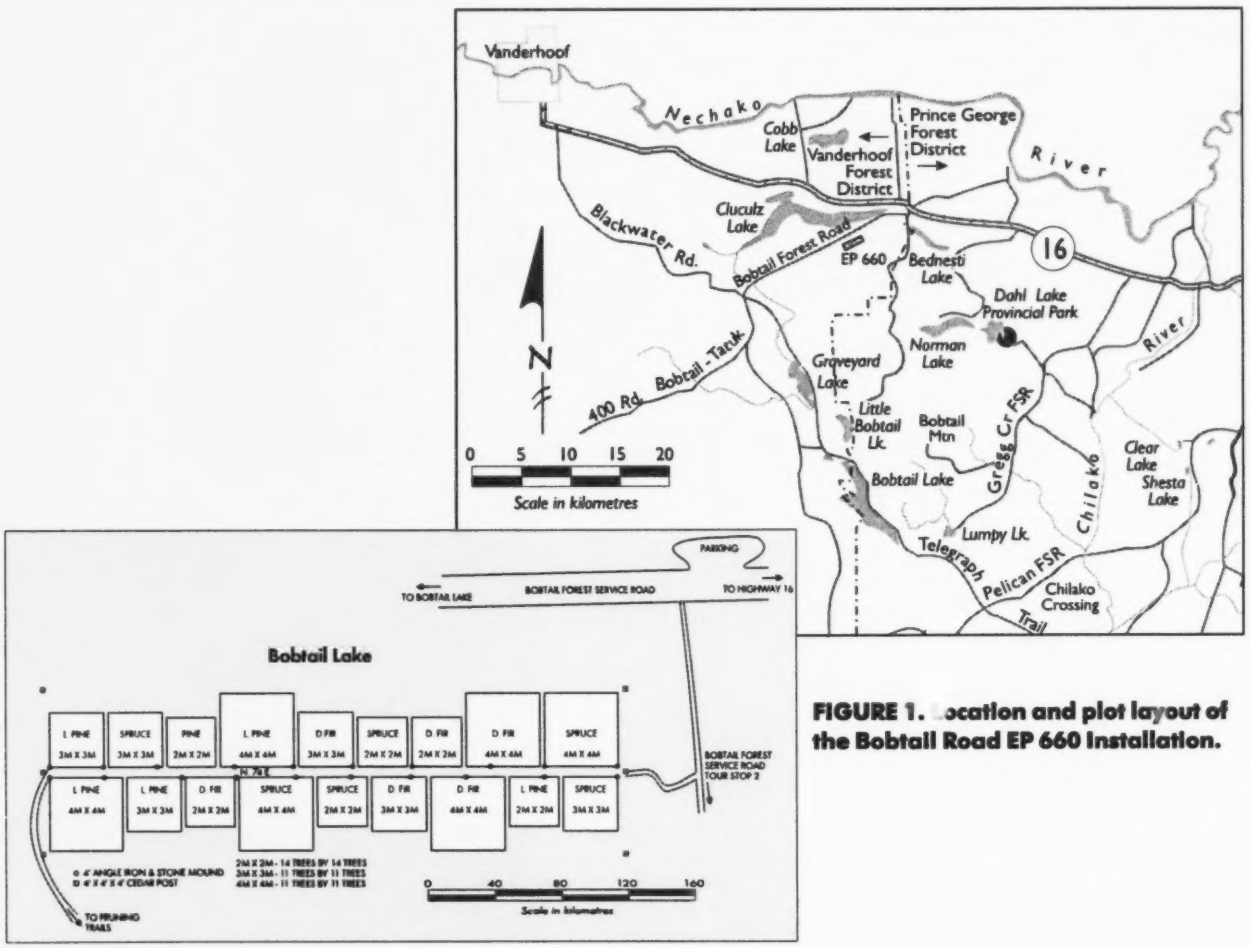


FIGURE 1. Location and plot layout of the Bobtail Road EP 660 Installation.

The Bobtail Road study area is one of three EP 660 installations surrounding Prince George. These three study installations were created at the same time using the same experimental methodology and planting stocks. Details on the EP 660 study rationale and methodology are reported in Research Note PG-12 (Coopersmith *et al.* 1997a). Results from the Buckhorn Ridge trial are summarized in Research Note PG-12-1 (Coopersmith *et al.* 1997b), while those for the Chilco Creek installation are summarized in Research Note PG-12-3 (Coopersmith *et al.* 1998) in this same series.

The Bobtail Road Study Area

The Bobtail Road trial of EP 660 is contained within the Cluculz Lake Silviculture Demonstration Area, an area of varied silviculture trials in use since 1964. The trial is located at km 20 of the Bobtail Forest Service Road and is located in the Vanderhoof Forest District (Figure 1). The study plots straddle district lots 4970 and 4971 (123° 30'W, 53° 51'N). Mean elevation of the study area is approximately 840 m. The study area is classified within the sub-mesic to mesic white spruce - Douglas-fir - Rice grass site series of the Stuart dry warm Sub-Boreal Spruce biogeoclimatic sub-zone ($SBS_{dw3/04}$, DeLong *et al.* 1993). Prickly rose (*Rosa gymnocarpa* Nutt.) and Sitka mountain alder (*Alnus viridis* [Chaix] DC. spp. *sinuata* [Regel] Love and Love) are the dominant shrubby vegetation on site. Soils underlying the study area consist of Brunisolic Gray Luvisols and Orthic Gray Luvisols belonging to the Deserters Soil Association (Dawson 1989). The Deserters soil association is one of the most common soil associations occurring on land forms between Prince George and Vanderhoof. It occurs on land forms composed of basal till that have been deposited and moulded by glacial ice. Drumlins of various sizes account for the hilly nature of the study location. The glacial till is medium to moderately fine textured gravely loams to gravely clay loams, although this is highly variable within the study plots. In places the soils are very gravely and stones are common throughout. The rooting depth of the soils is shallow, generally less than 50 cm. The plots slope gradually (less than 5 %) to the northwest.

The area was clearcut logged in the early Winter of 1964-65 and broadcast burned in the late Fall of 1965. This was one of the first operational applications of prescribed burning following logging in the Vanderhoof district. Most of the area was left for natural regeneration, presumably for lodgepole pine. An interesting mix of pine and trembling aspen now occupies much of the area surrounding the trial. The study plots were laid out and planted in 1967.

Study Design and Measurement Schedule

The EP 660 trial uses a factorial design. Three planting espacements (factor 1; 2m x 2m or 2197 sph, 3m x 3m or 1076 sph, and 4m x 4m or 637 sph) were used for each of the three species (factor 2; lodgepole pine, white spruce and Douglas-fir). This 3 x 3 design results in 9 treatment combinations per replicate. Two replicates of 9 plots were used at each installation, resulting in 18 plots per installation (Figure 1). Treatments were assigned to plots randomly within replicates.

Treatments were planted as either 11 rows by 11 rows or 14 rows by 14 rows depending upon available space. However assessments were confined to the central 7 rows by 7 rows of trees, or 49 trees per species x spacing x replicate combination. This meant that the measurement plots were surrounded by a minimum of two and a maximum of four buffer rows per plot. The plantation was measured in 1977 (year 10), 1981 (year 15), 1986 (year 20), 1991 (year 25) and 1996 (year 30). However, growth measurements were adjusted by 2 years (for lodgepole pine and Douglas-fir) or by 3 years (for white spruce) to account for time since germination in the nursery. Analysis of height and diameter growth for the trial was performed using a repeated measures analysis of variance (ANOVA) procedure. Basal areas (outside bark) were calculated from measured diameters using standard formula (Wenger 1984). Total tree volumes were calculated using the equations for juvenile trees from Kovats (1977).

Complete brushing and weeding of the plots and boundaries took place in 1979, 1983, 1986 and 1996/97. During the first measurement in 1977 the trees were not numbered. In 1981, the study trees were tagged, but many of these original tags were lost. All trees in the plots were re-tagged in 1986. However, the pattern of live and dead trees within the plots dating back to 1981 has allowed us to positively match trees between measurement years regardless of lost tag number.

In the fall of 1997, the Douglas-fir at the Bobtail Road installation were pruned to a height of 3 m, or to 50% of their live crown height where total height was less than 6 m. Both pruning saws and pruning shears were used, although the shears proved ineffective for the very large branch diameters in most of the stand and were soon discarded. The pruning saws, although slower than the shears, could reach much easier to the desired 3 m height and produced a much cleaner cut and smaller branch nub. Pruning was done to allow tag numbers to be attached at breast height to tree boles with 3 inch zinc-coated box nails, and to facilitate easier

site visits and measurements which were becoming difficult because of the thick tangle of branches in most plots. Prior to the pruning, the tags on the Douglas-fir were strung from the lower branches with wire. Most of these lower branches were dead, and some tags have been lost as these branches broke. The lodgepole pine on site were pruned in 1986. A similar pruning operation is currently planned for the white spruce plots in 1998.

Results

Table 1 and Figures 2 through 5 summarise the changes in height and diameters and calculated volumes and basal areas that have been observed at Bobtail Road since 1967. Table 2 summarises the findings of the repeated measures Anova for changes in height and diameter with species and spacing at Bobtail Road.

Effects of Species and Spacing on Top Height and Quadratic Mean Diameters

The stands at Bobtail Road appear to be well stratified by species in terms of both top height (P›.000, Table 2) and quadratic mean diameter (P›000, Table 2) (Top height is defined as the average height of the 10 tallest trees per hectare, Quadratic mean diameter is the diameter of the tree of average basal area, Daniel *et al.* 1979). Not surprisingly, lodgepole pine contains on average both the tallest and the largest diameter trees in the plantation, followed by Douglas-fir and white spruce. The tallest individual lodgepole pine are now more than 24 m tall with top heights between 13 and 14 m depending upon espacement (Figure 2a). By comparison the tallest Douglas-fir at Bobtail Road are now 26 m tall, however mean top heights for Douglas-fir are between 10 m and 12 m (Figure 2b). The Douglas-fir at the Bobtail installation suffered significant amounts of top dieback (probably as a result of frost) some 8 to 10 years ago. Where individual trees managed to escape this abiotic event, top heights are now equal to or exceed those of lodgepole pine. However, in general the damage to the Douglas-fir stands was widespread enough to significantly lower the mean plot heights and top heights of all Douglas-fir on site. The tallest white spruce were measured at just under 20 m height with average top heights of between 9 m and 10 m (Figure 2c).

In comparison to top heights, there were smaller differences between species for quadratic mean diameters. Lodgepole pine again had the largest quadratic mean diameters, varying between approximately 13.5 cm and 17.1 cm depending upon espacement (Figure 3a). Douglas-fir was not a great deal smaller, with quadratic mean diameters ranging between 12.3 cm and 16.4 cm (Figure 3b). White spruce was again much smaller than either lodgepole pine or Douglas-fir, with quadratic mean diameters between 8.5 cm and 13.0 cm (Figure 3c).

In contrast to the more obvious species effect observed at the Bobtail Road installation, initial spacing did not have as dramatic an effect on average height (p›.039, Table 2). Although still statistically significant, of the three species only Douglas-fir seemed to exhibit a strong espacement effect on height growth, with the tallest trees being found in the highest density 2m x 2m espacement. After 30 years, there is virtually no difference in the top heights between espacements for either lodgepole pine or white spruce. This reinforces the common silvicultural observation that height growth (and thus site index) is set more by climate and soil than it is by plantation density, except at the extremes (both high and low) of stand density (Daniel *et al.* 1979).

Spacing did have a very strong influence on quadratic mean diameters however (P›000, Table 2). For all three species, quadratic mean diameters were inversely related to density. The largest quadratic mean diameters were found in the lowest density 4m x 4m espacement plots, followed respectively by the 3m x 3m and the 2m x 2m plot quadratic means. This same relationship has been shown for all commercial forest species in North America (Daniel *et al.* 1979).

Basal Area and Volume Changes Over Time

Since basal area is directly related to diameter, it is not surprising that the basal area development of lodgepole pine and Douglas-fir are very similar at Bobtail Road (Figure 3). It is similarly not surprising that the highest density plots have the greatest calculated basal areas. In the highest density 2m x 2m plots, Douglas-fir basal area (27.22 m^2/ha) now surpasses lodgepole pine basal area (26.17 m^2/ha). We continue to observe additional mortality, principally in the lodgepole pine plots. A number of the lodgepole pine have stem infections of Western Gall Rust (*Endocronartium harknessii* [J.P. Moore] Y. Hirat). Although branch galls are the more commonly observed infection vector for this disease, they are rarely fatal. However, where the galls form on the stem, mortality does occur, often decades after the initial infection (Finck *et al.* 1987). The infected tree can be killed either directly by the complete girdling of the stem by the gall, or by wind-breakage at the canker-weakened point (the more common phenomenon observed in the Bobtail Road plots). Since the 1991 evaluation where 83 live trees were measured in the 2m x

2m lodgepole pine plots, there have been 3 additional dead trees recorded. All three of these trees were broken by wind at stem cankers. Since trees infected with stem cankers can reach substantial diameters before they die, the loss of these trees does significantly affect the calculation of both basal area and volume. By comparison, there has been no recorded mortality in the closest espacement Douglas-fir plots since 1981.

The rate at which new basal area is being added to the lodgepole pine plots appear to have peaked, perhaps as early as the 15 year evaluation in 1981 for the 2m x 2m plots (Figure 4a). For both Douglas-fir and white-spruce however, there is no sign yet that their rates of basal area increment have slowed (Figures 4b and 4c).

Lodgepole pine plots contain substantially greater total volumes compared with both Douglas-fir and white spruce. Average total volumes in the 2m x 2m lodgepole pine are now approaching 95 m^3/ha compared with approximately 48 m^3/ha for Douglas-fir and only 20 m^3/ha for white spruce (Figure 5, Table 1). Mean annual increments for the highest density lodgepole pine plot are now more than 3 m^3/ha/yr, nearly twice that of Douglas-fir (1.6 m^3/ha/yr) and nearly five times that of white spruce (0.6 m^3/ha/yr). Since volume calculations utilise both height and diameter components, the greater height of lodgepole pine would on average account for the greater observed amounts of volume for this species.

Only the highest density 2m x 2m lodgepole pine plots have 5-year periodic annual increments (PAI's) for the 1991-96 time period that are less than their 1986-91 values. The PAI for these lodgepole pine plots went from 6.17 m^3/ha/yr in 1986-91 to 4.09 m^3/ha/yr in the period 1991-96. PAI's are known to peak before MAI's do. Peaking of PAI's is often cited by silviculturist as the point at which the stand is entering the "stem exclussion" phase of stand development. This is the period within which mortality due to inter-tree competiton can be expected (Oliver and Larson 1990). The 1991-96 calculated PAI's for all other species and espacements combinations at Bobtail are still increasing relative to the 1986-91 incremetns.

Photo 3: Although initially a slow starter, the white spruce plantings at Bobtail road are now growing extremely well.

Photo 4: Even at the higher densities, the open canopies of lodgepole pine allow a great deal of light to reach the forest floor. A very diverse mix of shrubs and herbs can be found on these plots.

Comparison of Stand Density Indexes at Bobtail

It is often times difficult to compare the growth rates of stands of different species grown at different densities. This problem is often tackled by using various relative density measures or stand density indexes which are independent of site and age (Larson and Cameron 1986). Two of the most useful indexes are Reineke's Stand-Density Index (SDI) (Reineke 1933, [in Daniel *et al.* 1979]) and Curtis's relative density (RD) (Curtis 1982).

SDI is the oldest of the indexes and is probably the most commonly used in growth and yield literature. Reineke observed that all single-species, even-aged, fully stocked stands of the same quadratic mean diameter will have approximately the same number of stems/ha regardless of site quality or stand age (Daniel *et al.* 1979). Stands will differ in the amount of time necessary to reach a given quadratic mean diameter. Better quality sites will produce trees of larger diameter faster than will poorer sites. However, when they reach the same quadratic mean diameter, they will all have the same approximate density. The relationship of the natural log of density to the natural log of quadratic mean diameter has a near constant slope of -1.605 for many forest species (Larson and Cameron 1986) and can be used to compare stands at various stages of development. SDI for a given stand is the number of trees at equivalent relative density when the average dbh is 25 cm. For coastal Douglas-fir, the maximum observed SDI is 1510 trees/ha while several species of pine ranged in SDI

values from a low of 1015 trees/ha (longleaf pine [*Pinus palustris* Mill.]) to a high of 2106 trees/ha (Ponderosa Pine [*Pinus ponderosa* Doug. ex Lawson & Lawson]) (Larson and Cameron 1986).

SDI has increased steadily in all plots at Bobtail Road since the first measurements in 1977 (Table 1). The maximum SDI observed at the Bobtail Road site was 722 sph for the 2m x 2m lodgepole pine plots. Only the SDI for the 2m x 2m Douglas-fir plots (677 sph) are close to the values for the lodgepole pine plots. All other SDI values are approximately half of these values or less. The SDI's observed at Bobtail are still well below the listed maximum found in the literature for Ponderosa pine, the pine species most similar to lodgepole pine. This should mean that the stands at Bobtail will continue to grow with little additional mortality due to intra-species competition. Tree mortality will continue at Bobtail Road however, especially in the lodgepole pine plots as a result of gall rust infections.

Curtis's relative density measurement is similar to SDI except that it uses basal area and quadratic mean diameter in its' calculation. Values of RD range from 0 to 14 for coastal Douglas-fir. Like SDI, values of RD tend to increase over time, but can fluctuate widely as trees self thin. Because very small trees can remain alive for long periods of time, they can drastically affect RD calculations. Events such as a heavy wind storms or dry summers, which tend to remove the smallest and most moribund individuals within stands first, can cause very marked jumps in SDI (Larson and Cameron 1986).

At Bobtail, the Douglas-fir 2m x 2m plots had the highest RD at 7.62, followed closely by 2m x 2m lodgepole pine at 7.09 (Table 1). The highest RD for white spruce was 4.13 again for the 2m x 2m plots. The values for the 3m x 3m and 4m x 4m plots were all approximately one half or less of the values for the 2m x 2m plots for each species respectively. As for SDI, the observed RD values are still well below the values where we would expect to see self-thinning losses due to intra-species competition. Larson and Cameron (1986) ran a simulated thinning experiment through the Tree and Stand Simulator model (TASS, Mitchell 1975). Starting with a plot of Douglas-fir planted to 1110 sph (3m square spacing) they thinned (by low thinning) to 361 sph at age 32 and 158 sph at age 47. At the time of the first thinning RD was 7.2. The first thinning reduced RD to 3.3. It subsequently recovered to 5.5 at the time of the second thinning, and was again reduced, this time to 2.7 by the second operation.

Future Lumber Values

One of the advantages of utilising higher plantation densities is that the live crowns of closely-planted stands lift faster than the live crowns in widely-spaced stands. The lower boles of densely planted stands have smaller branches and subsequent smaller knots when these branches die. The smaller live crown of very dense stands produce lower percentages of juvenile wood which normally translates to higher wood quality (Cannell 1985).

The crowns of Douglas-fir at Bobtail are the densest of the 3 species in this trial. In the 2m x 2m plots (2196 sph initial density) and the 3m x 3m plots (1076 sph initial density), the live crowns on most of the trees start at between 3 m and 5 m above the root collar. These stands are very dark, with little in the way of undergrowth beneath them. The widest espacement Douglas-fir generally have live branches at or near the root collar, and the lowest live branches on these trees are exceeding large (generally greater than 5 cm).

The crowns of lodgepole pine have also lifted dramatically in the 2m x 2m plots. In these plots, live crowns are now confined to crown positions between 5 m and 9 m above root collar. However, as density decreases, the live crown for this species increases dramatically. In both the 3m x 3m and the 4m x 4m plots there are live lower branches that start at the first branch (approximately 2 m after the 1986 pruning). Many of these branches now extend more than 3.5 m from the bole of the tree. Many branch diameters are now as large as 8 cm.

The crowns in the white spruce stands have not lifted appreciably in the first 30 years of the trial. Most trees have live crowns that extend to the ground. However, unlike Douglas-fir and white spruce, most of the lowest live branches in spruce are quite small, the crowns are very columnar, and the branch diameters are not exceedingly large.

Despite the crown lift observed for both Douglas-fir and lodgepole pine at higher densities, there has been little natural pruning of branches in these stands. Dead branches of both species had to be manually pruned in order to produce clear boles.

Conclusions

- Currently there are clear differences between the 3 species in terms of top height over the first 30 years of the EP 660 trials at Bobtail Road. Lodgepole pine is the tallest species on site, followed by Douglas-fir and white spruce respectively. Much of this difference in top height between Douglas-fir and lodgepole pine can be attributed to abiotic events (probably frost) which have damaged the Douglas-fir on site more heavily than either of the other two species.

- There are much smaller species differences for quadratic mean diameters than for height. In fact, Douglas-fir is now the largest tree on site in terms of QMD followed closely by lodgepole pine. White spruce continues to lag behind the former two species in terms of both height and diameter growth.

- Abiotic damage (probably frost) has affected virtually every Douglas-fir at Bobtail Road. This has resulted in substantial height growth losses in these stands. We are not sure if the seedlot of Douglas-fir used in the EP 660 trial was particularly frost-prone, or if the Bobtail Road site is an exceptionally frost-prone area for this site series. However, it does raise a red flag for any forester contemplating using Douglas-fir in this area. If frost-hardy stock is available however, the growth rate of Douglas-fir that we have observed at Bobtail Road, its' resistance to common pests and pathogens relative to other species like lodgepole pine, and the potential value of lumber derived from this species make it a very attractive alternative to either lodgepole pine or white spruce on the right site.

- We continue to loose approximately 0.5 % of lodgepole pine every year to wind snap at gall infection points on stems. Overall survival of lodgepole pine at Bobtail is now approximately 85 per cent. However, most of the lodgepole pine at Bobtail Road have branch galls on them, and a substantial number also have stem galls. The losses in these stands will continue well into the foreseeable future. Forest managers must account for the long-term susceptibility of this species to mortality agents such as gall rust by developing and using disease-resistant stock types, keeping plantation densities high or encouraging additional natural regeneration of pine at the time of plantation establishment. Considering all of the pests and pathogens that can effect this species (often occurring decades after initial plantation establishment), target stocking levels and acceptable minimum stocking levels in regional stocking standards should be raised substantially for lodgepole pine.

- Although the live crowns of both lodgepole pine and Douglas-fir are now lifting in the two highest density treatments, the lowest branches (whether live or dead) in these stands now have very large diameters. These large lower branches will result in very large knots, significantly lowering the future wood quality that can be achieved from these stands. The crowns of all three species in the lowest density plots extend almost to the ground. Since these plots are very close to target minimum stocking levels from the Prince George regional stocking standards (generally between 700 and 1200 stems/ha, Anonymous 1993), we should not expect the crowns to lift quickly in any stands within the region that are grown at or close to minimum stocking levels. Stand densities should be high enough to cause the crowns of Douglas-fir and lodgepole pine to lift quickly, limiting the size of knots If future wood quality is perceived to be an important issue within the Prince George region, then higher target and minimum stocking densities must become standard.

- The stand densities tested at the Bobtail Road installation were not high enough to induce natural pruning in any of the three species tested. Given the target and minimum stocking standards of current planting in the Prince George region, manual pruning will be necessary in most plantations if clear wood is the objective.

Photo 5: Brushing must be done at regular intervals to keep the brush at bay. Co-op student Bruce Rogers mans the brush saw in one of the EP 600 plots.

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For more information contact:

Dave Coopersmith, RPF. Research Silviculturalist
Prince George Forest Region
1011-4th Avenue, Prince George, BC, V2L 3H9
phone: 250-565-6100 fax: 250-565-4349
email: dcoopers@gems3.gov.bc.ca

Table 1: Summary of the 30 year measurements for all 3 species at the Bobtail Road Installation of EP 660.
A: Lodgepole Pine

Year	1977			1981			1986			1991			1996		
spacing (m)	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4
age from seed (years)	12	12	12	17	17	17	21	21	21	26	26	26	31	31	31
sample n	96	95	96	90	85	92	87	88	92	83	79	91	80	80	90
stems/ha	2153	1044	624	2018	934	598	1951	967	598	1861	868	592	1794	879	585
average ht. (m)	3.43	3.45	2.98	6.27	6.00	5.31	8.29	8.00	7.24	10.86	10.87	9.56	11.68	11.95	11.27
(se)	(0.11)	(0.12)	(0.11)	(0.20)	(0.20)	(0.19)	(0.24)	(0.24)	(0.23)	(0.42)	(0.43)	(0.40)	(0.41)	(0.38)	(0.38)
top height[2] (m)	4.68	4.55	4.03	8.07	7.29	6.69	9.96	9.38	8.76	13.33	12.58	11.49	13.63	13.62	13.35
(sd)	(0.24)	(0.17)	(0.37)	(0.51)	(0.46)	(0.37)	(0.03)	(0.33)	(0.23)	(0.25)	(0.37)	(0.33)	(0.69)	(0.25)	(0.39)
sample n[1]			95		70										
arithmetic mean															
diameter (cm)	1.47	1.57	1.37	8.23	8.91	8.47	10.49	12.11	11.59	12.16	14.48	14.75	13.48	16.05	17.06
(se)	(0.12)	(0.12)	(0.12)	(0.28)	(0.34)	(0.28)	(0.40)	(0.40)	(0.39)	(0.41)	(0.42)	(0.39)	(0.38)	(0.38)	(0.35)
quadratic mean															
diameter (qmd) (cm)	1.51	1.67	1.43	8.39	9.06	8.68	10.65	12.25	11.88	12.32	14.65	15.03	13.63	16.29	17.36
basal area (m^2/ha)	0.38	0.23	.10	11.17	4.97	3.54	17.38	11.41	6.63	22.18	14.63	10.49	26.17	18.33	13.85
Relative Density (RD)															
($ba/qm^{1.5}$)	0.31	0.18	0.08	3.86	1.65	1.20	5.33	3.26	1.92	6.32	3.82	2.71	7.09	4.54	3.32
Reineke's SDI	23.80	13.57	6.32	349.84	183.17	109.5	495.97	307.75	181.2	597.7	368.13	261.61	677.63	442.01	325.79
Total Volume (m^3/ha)	0.45	0.27	0.1	20.99	8.74	5.52	43.39	26.67	14.24	74.24	45.77	30.06	94.69	65.86	46.92
mean annual															
increment (MAI)	0.038	0.023	0.008	1.235	0.514	0.325	2.066	1.270	0.678	2.855	1.760	1.156	3.055	2.125	1.514
(m^3/ha/yr)															
5-year periodic annual															
increment (PAI)				4.108	1.694	1.084	4.480	3.586	1.744	6.170	3.820	3.164	4.090	4.018	3.372
(m^3/ha/yr)															

[1]Where no sample number is given, n is the same for both average height and arithmetic mean diameter calculations. Where a second n is given, the second n refers only to sample number for the arithmetic mean diameter calculation.

[2]Top height calculations are averages of the 100 tallest trees/ha. For the 2m x 2m treatments, this equals the tallest 4 trees in the 2 replicates. For the 3m x 3m plots, the average is based on the tallest 9 trees. While for the 4m x 4m plots, this average is based on the tallest 15 trees.

Table 1: Continued. **B: White Spruce**

Year	1977			1981			1986			1991			1996		
spacing (m)	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4
age from seed (years)	13	13	13	18	18	18	22	22	22	27	27	27	32	32	32
sample n	98	96	98	96	93	95	96	96	95	96	92	95	96	91	95
stems/ha	2196	1055	637	2153	1022	618	2153	1055	618	2153	1011	618	2153	1000	618
average ht. (m)	1.25	1.19	1.33	2.12	2.31	2.59	3.07	3.57	4.00	4.24	5.15	5.57	5.78	6.85	7.52
(se)	(0.11)	(0.11)	(0.11)	(0.19)	(0.19)	(0.19)	(0.23)	(0.23)	(0.23)	(0.39)	(0.40)	(0.39)	(0.37)	(0.38)	(0.37)
top height[2] (m)	2.38	2.03	1.85	4.03	3.85	3.65	5.61	5.60	5.44	7.68	7.62	7.62	9.05	9.54	9.73
(sd)	(0.38)	(0.27)	(0.23)	(0.23)	(0.21)	(0.54)	(0.43)	(0.35)	(0.61)	(0.48)	(0.38)	(0.38)	(0.38)	(0.48)	(0.74)
sample n[1]				84	84	93	92	92		95			95		
arithmetic mean															
diameter (cm)				2.20	2.50	2.86	3.88	4.59	5.53	5.81	7.49	9.05	8.05	10.52	12.63
(se)				(0.29)	(0.29)	(0.28)	(0.39)	(0.39)	(0.38)	(0.38)	(0.39)	(0.38)	(0.35)	(0.35)	(0.35)
quadratic mean															
diameter (qmd) (cm)				2.53	2.83	3.11	4.24	4.98	5.85	6.25	7.92	9.40	8.48	10.92	12.99
basal area (m^2/ha)				0.94	0.57	0.46	2.91	1.97	1.66	6.52	4.98	4.29	12.04	9.47	8.18
Relative Density (RD)															
(ba/$qm^{4.5}$)				0.59	0.34	0.26	1.41	0.88	0.69	2.61	1.77	1.40	4.13	2.87	2.27
Reineke's SDI				54.50	30.97	21.79	124.82	79.18	60.06	232.67	159.78	128.58	379.69	264.64	216.09
Total Volume (m^3/ha)				0.67	0.42	0.34	2.74	2.03	1.79	8.03	7.04	6.22	19.57	16.71	15.65
mean annual															
increment (MAI)				0.037	0.023	0.019	0.125	0.092	0.081	0.297	0.261	0.230	0.612	0.522	0.489
(m^3/ha/yr)															
5-year periodic annual															
increment (PAI)				0.134	0.084	0.068	0.414	0.322	0.290	1.058	1.002	0.886	2.308	1.934	1.886
(m^3/ha/yr)															

[1]Where no sample number is given, n is the same for both average height and arithmetic mean diameter calculations. Where a second n is given, the second n refers only to sample number for the arithmetic mean diameter calculation.

[2]Top height calculations are averages of the 100 tallest trees/ha. For the 2m x 2m treatments, this equals the tallest 4 trees in the 2 replicates. For the 3m x 3m plots, the average is based on the tallest 9 trees. While for the 4m x 4m plots, this average is based on the tallest 15 trees.

Table 2: Summary of the repeated measures analysis of variance (ANOVA) for height and diameter growth differences for the 3 species and 3 spacings at Bobtail Road. The repeated measures ANOVA was given REPxSPECIESxSPACING means as input terms rather than individual tree data in order to get the correct error term in the model. The reported F values and probability tests are for the Wilkes-Lambda test which is the correct F test for repeated measures analysis. Because only lodgepole pine has DBH recorded for the 1977 measurement, the repeated measures analysis was done on the 1981-1996 data. This results in reduced degrees of freedom (df) for this portion of the analysis. Analysis for height was done with 1977 to 1996 data.

Source	Sum of Squares	df	MeanSquare	F value	Probability[1]
DBH					
Year	676.519	3	225.506	9292.619	0.000
Year*Species	15.291	6	2.549	48.607	0.000
Year*Spacing	25.397	6	4.233	31.30	0.000
Year*Species*Spacing	1.127	12	0.094	3.480	0.008
Error	0.971	27	0.036		
Height					
Year	516.113	4	129.028	1520.754	0.000
Year*Species	22.248	8	2.781	18.290	0.000
Year*Spacing	1.330	8	0.166	3.068	0.039
Year*Species*Spacing	2.401	16	0.150	1.821	0.106
Error	2.336	36	0.065		

[1]Probabilities less than 0.05 are considered significant

Table 1: Continued. **C: Douglas-fir**

Year	1977			1981			1986			1991			1996		
spacing (m)	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4	2x2	3x3	4x4
age from seed (years)	12	12	12	17	17	17	21	21	21	26	26	26	31	31	31
sample n	98	91	97	95	87	96	95	87	95	95	86	95	95	86	95
stems/ha	2197	1000	631	2130	956	624	2130	956	618	2130	945	618	2130	945	618
average ht. (m)	1.96	1.61	1.85	3.86	3.13	3.63	5.59	4.55	5.32	7.29	6.12	7.25	8.35	7.25	8.71
(se)	(0.11)	(0.12)	(0.11)	(0.19)	(0.20)	(0.20)	(0.23)	(0.24)	(0.23)	(0.39)	(0.41)	(0.39)	(0.37)	(0.39)	(0.37)
top height[2] (m)	3.53	2.63	2.87	6.34	4.92	5.50	8.63	9.11	7.57	10.90	9.26	9.95	11.88	10.37	11.42
(sd)	(0.35)	(0.17)	(0.29)	(0.40)	(0.24)	(0.34)	(0.46)	(0.83)	(0.43)	(0.50)	(0.48)	(0.39)	(0.50)	(0.70)	(0.57)
sample n[1]					83	94									
arithmetic mean															
diameter (cm)				4.58	3.94	4.75	7.51	6.49	8.00	10.42	10.54	12.61	12.25	12.97	16.42
(se)				(0.28)	(0.30)	(0.28)	(0.38)	(0.40)	(0.38)	(0.38)	(0.41)	(0.38)	(0.35)	(0.38)	(0.35)
quadratic mean															
diameter (qmd) (cm)				5.03	4.31	5.21	7.96	7.02	8.69	10.83	11.04	13.29	12.75	13.53	17.16
basal area (m^2/ha)				4.22	1.33	1.30	10.61	3.62	3.67	19.62	8.93	8.57	27.22	13.58	14.28
Relative Density (RD)															
(ha/qm$^{4.5}$)				1.88	0.64	0.57	3.76	1.37	1.25	5.96	2.69	2.35	7.62	3.69	3.45
Reineke's SDI				162.44	56.90	50.35	339.35	124.49	113.30	556.24	254.51	224.16	722.82	352.75	337.83
Total Volume (m^3/ha)				3.79	0.96	1.09	12.98	3.48	4.16	30.65	11.19	12.55	48.07	19.52	23.93
mean annual															
increment (MAI)				0.223	0.057	0.064	0.618	0.166	0.198	1.179	0.430	0.483	1.551	0.630	0.772
(m^3/ha/yr)															
5-year periodic annual															
increment (PAI)				0.758	0.192	0.218	1.838	0.504	0.614	3.534	1.542	1.678	3.484	1.666	2.276
(m^3/ha/yr)															

[1]Where no sample number is given, n is the same for both average height and arithmetic mean diameter calculations. Where a second n is given, the second n refers only to sample number for the arithmetic mean diameter calculation.

[2]Top height calculations are averages of the 100 tallest trees/ha. For the 2m x 2m treatments, this equals the tallest 4 trees in the 2 replicates. For the 3m x 3m plots, the average is based on the tallest 9 trees. While for the 4m x 4m plots, this average is based on the tallest 15 trees.

Table 3: Summary of the regression lines of best fit for height data at the Bobtail Road installation. The equations are all quadratic in form, indicating that height growth is no longer linear with age. The equations do not include a constant. In most instances, the fit was better without a constant (higher r^2 values). The equations also make more biological sense when they are fit through the origin rather that an intercept.

Effect	Level	Equation	r^2
species	lodgepole pine	$ht = 0.27(age) + 3.959x10^{-1}(age^2)$	0.99
	white spruce	$ht = 0.02(age) + 0.01(age^2)$	0.98
	Douglas-fir	$ht = 0.12(age) + 4.784x10^{-3}(age^2)$	0.99
spacing	2m x 2m	$ht = 0.19(age) + 2.865x10^{-3}(age^2)$	0.88
	3m x 3m	$ht = 0.15(age) + 4.293x10^{-3}(age^2)$	0.89
	4m x 4m	$ht = 0.13(age) + 0.01(age^2)$	0.94

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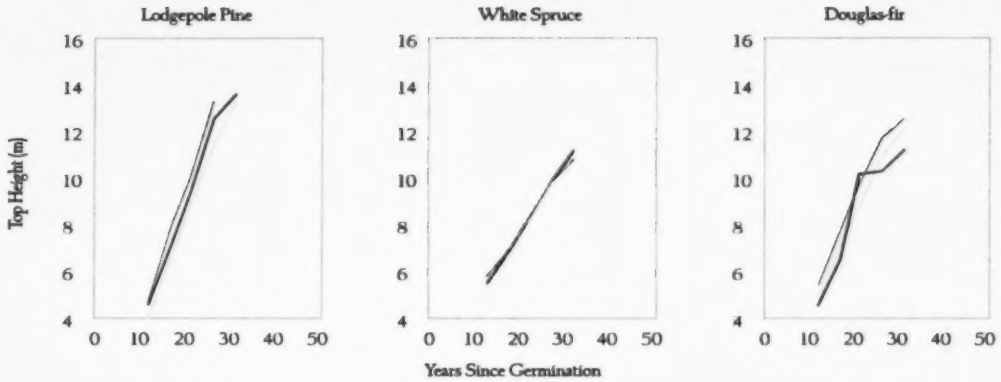

Figure 2. Changes in top height over time at the Bobtail Road Installation for a) lodgepole pine, b) white spruce and c) Douglas-fir.

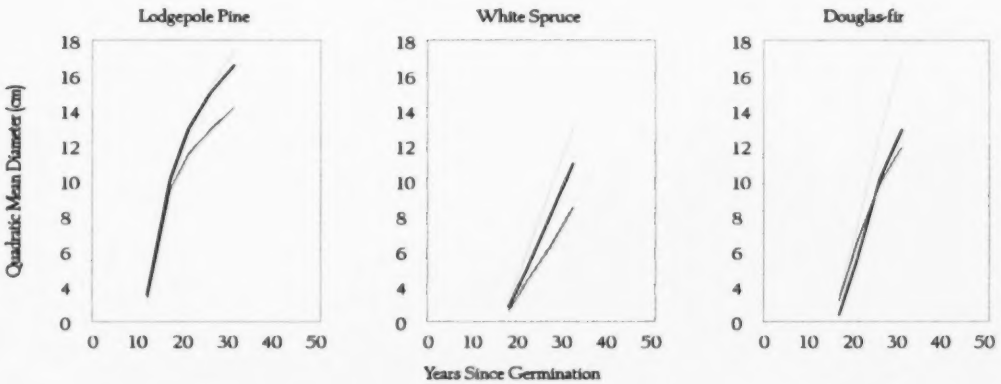

Figure 3. Changes in quadratic mean diameter over time at the Bobtail Road Installation for a) lodgepole pine, b) white spruce and c) Douglas-fir.

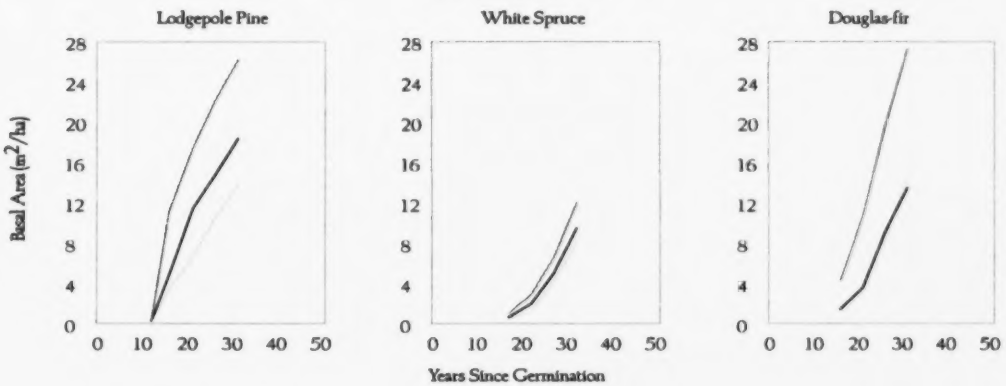

Figure 4. Changes in summed basal area over time at the Bobtail Road Installation for a) lodgepole pine, b) white spruce and c) Douglas-fir.

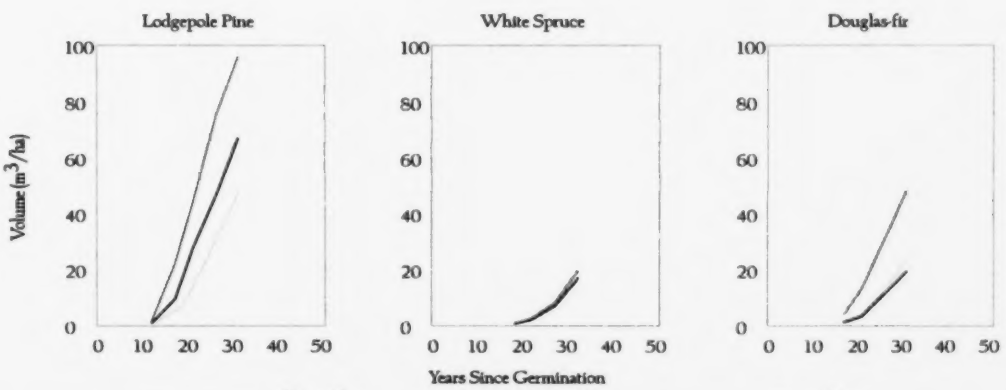

Figure 5. Changes in summed total volume over time at the Bobtail Road Installation for a) lodgepole pine, b) white spruce and c) Douglas-fir.